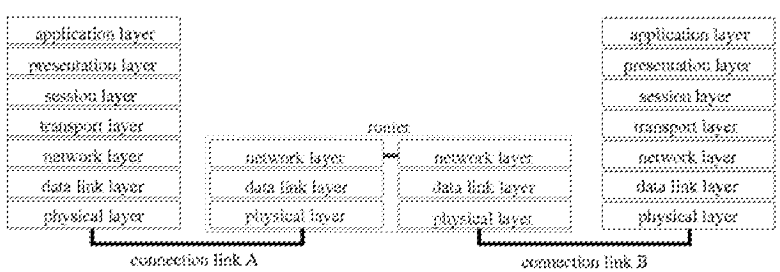
Chapter 5: Network Layer

1 Basics

- The **network layer** provides the means to transport messages from a source node over an **interconnection network** (IN) with several intermediate nodes to a destination node
- major **functions** in this layer:
  - routing, i.e. the selection of a transport path
    either *static* (fixed for all packets of a message) or *dynamic* (new path for each packet)
  - detection of overload situations
  - support of a logical addressing scheme
- famous example: IP

1 Basics (cont'd)

- A **router** operates on the network layer:
  - it can act as a junction between two or more networks to realize data transmissions among them
  - it allows the coupling of netwoks with different transmission media and different data link protocols



2 Interconnection networks

- each **IN** can be considered as a **graph** (V,E):
  - node set V consists of input/output nodes and internal switches
  - edge set $E \subseteq V \times V$ contains all interconnection links
  - each edge is characterized by a certain **data width** d and a **bit rate** $r \Rightarrow$ the resulting data rate is $b = d \cdot r$
  - the **degree** of a node is the number of incoming and outgoing edges
  - a **path** defines a way though a graph from an input node i to an output node j
  - the maximum distance between any two nodes in the graph is called **diameter** (measured in the number of *hops*)
  - the **cost** c is typically defined as the number of edges in the graph
- the graph determines the **topology** of a network

2 Interconnection networks (cont'd)

- some criteria for the evaluation of INs:
  - **transfer rate** r_{single} of a single connection link
    (often also called "*link bandwidth*")
  - **network throughput** r_{total} in a network of c connection links:
    $r_{total} = c \cdot r_{single}$
    (often also called "*network bandwidth*")
  - average or maximum latency between two network nodes
  - the **bisection width** w is the minimum number of connections links that must be cut through to divide the network into two subnetworks of approx. equal size
  - the **bisection throughput** $r_{\text{bisection}}$ is the throughput through the bisection cut: $r_{\text{bisection}} = w \cdot r_{single}$
    (often also called "*bisection bandwidth*")

2 Interconnection networks (cont'd)

- an interconnection network is built for connecting a certain number of **DTEs** (*Data Terminal Equipments*, e.g. telephones or computers)
- each IN can be realized as
  - a static network: the DTEs are directly coupled by point-to-point interconnection links
  - a broadcast network: all DTEs are connected to a shared transmission medium
  - a dynamic or switched network: the DTEs are connected via switches that allow to realize reconfigurable paths through the network

2 Interconnection networks (cont'd)

- one simple approach consists in coupling N DTEs by a network with **star** topology:
  - all DTEs are coupled by point-to-point links to a central node
  - the central node can be

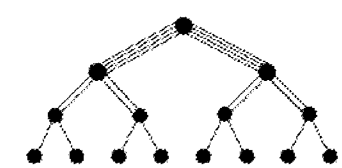
    1) **a computer** (DTE): all connections are realized in the DTE by hard- and software, central node can become a bottleneck
    ⇒ star network is a static network

    2) **a hub**: each incoming message is broadcasted to all nodes
    ⇒ star network is a broadcast network

    3) **a switch**: each incoming message is sent only to the destination node, many messages as possible should be switched simultaneously
    ⇒ star network is a dynamic network

2.1 Static interconnection networks

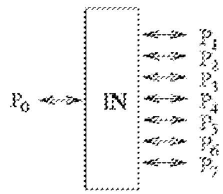
- some **topologies** for static networks:
  - full mesh: ideal network, each of the N nodes is directly connected to all other nodes, requires $N(N-1)/2$ links ⇒ impracticable
  - partial mesh
  - star
  - tree
  - fat tree →
  - grid
  - linear array
  - ring
  - hypercube



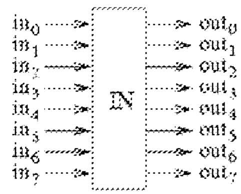
- each network of N nodes with static topology can be described by a (in general binary) $N \times N$ **interconnection matrix**

2.2 Dynamic interconnection networks

- Each dynamic interconnection network consists of internal **communication links** and **switches**
- there is at least one path from each input i to each output j
- each **bidirectional** dynamic interconnection network with N ports can be considered as an **unidirectional dynmaic** network with N inputs and N outputs:



simple telephone network for 8 participants



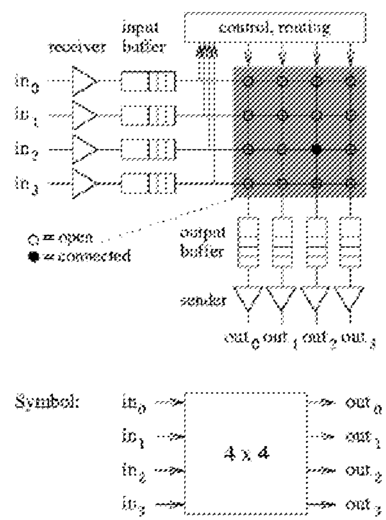
general network problem

2.2 Dynamic interconnection networks

- the cost of a dynamic network is often defined as the number of binary switches (*crosspoints*)
- dynamic networks can be classified as
  - **non-blocking**: each connection from a free input i to a free output j can always be realized
  - **blocking**: a path from a free input i to a free output j can not be realized, if a required internal connection link is already busy
  - **rearrangable**: each connection from a free input i to a free output j can be realized by rearranging one or several other already existing paths

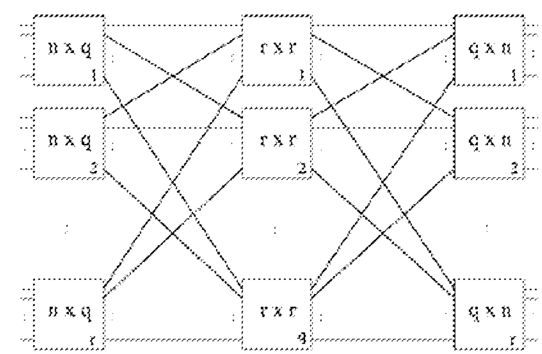
2.2 Dynamic interconnection networks (cont'd)

- an $N \times N$ **crossbar** is a single-stage non-blocking dynamic IN
- architecture, here for N=4: ⟶
- internal data width w
- trivial routing algorithm
  (the destination in the packet header is the index of the crossbar output)
- allows the realization of arbitrary permutations
  (in principle also all broadcast connection patterns are possible!)
- high cost: $O(N^2)$



2.2 Dynamic interconnection networks (cont'd)

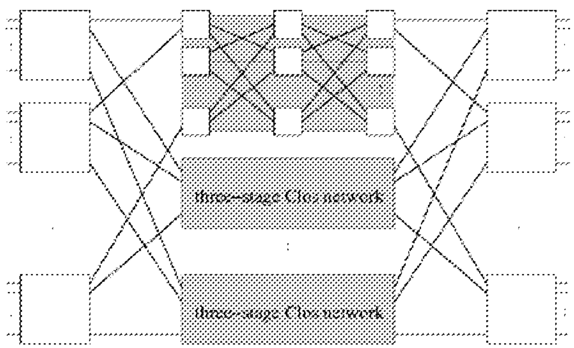
- *Idea*: The number of switches can be reduced by constructing multi-stage networks of small crossbar switches
- Architecture of a a **three-stage Clos network**:
  (Charles Clos, 1953)



- A Clos network is **non-blocking**, if $q \geq 2n$-1

2.2 Dynamic interconnection networks (cont'd)

- Cost of a three-stage Clos network with N inputs/outputs:
  $C_{Clos3} = 6\,N^{3/2} - 3N \quad \longrightarrow \quad O(N^{3/2})$
- Construction of a five-stage Clos network:

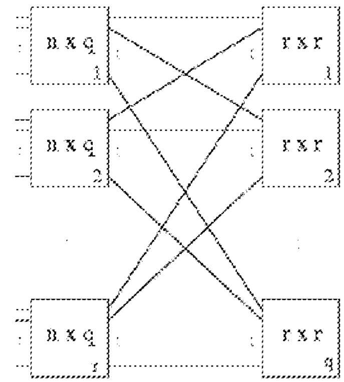


- Cost of a five-stage Clos network:
  $C_{Clos5} = 16\,N^{4/3} - 14N + 3\,N^{2/3} \quad \longrightarrow \quad O(N^{4/3})$

2.2 Dynamic interconnection networks (cont'd)

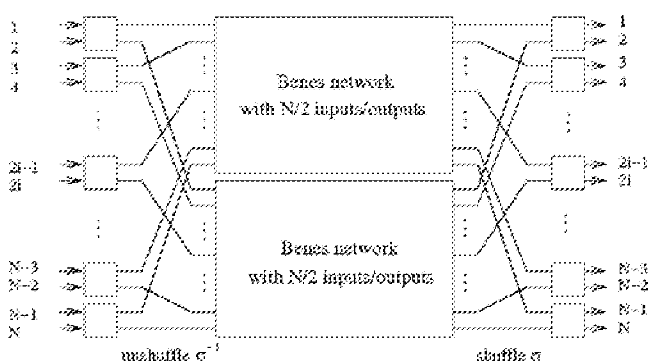
- Clos networks represent one of the most important dynamic network architectures
- In practice, Clos networks are realized with **bidirectional** interconnection links
  ⇒ **one-sided** Clos network
- same characteristics as a two-sided unidirectional Clos network
  (because it can be regarded as two-sided Clos network folded at the middle vertical axis)

  ⇒ also non-blocking for $q \geq 2n - 1$



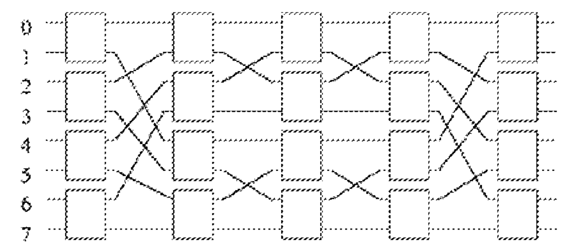
2.2 Dynamic interconnection networks (cont'd)

- A Clos network with $n = q$ is called a **Beneš network** (named after V. Beneš, 1962)
- It is typically shown in its recursive representation with binary switches ($n = 2$ and $N = 2^k$):



2.2 Dynamic interconnection networks (cont'd)

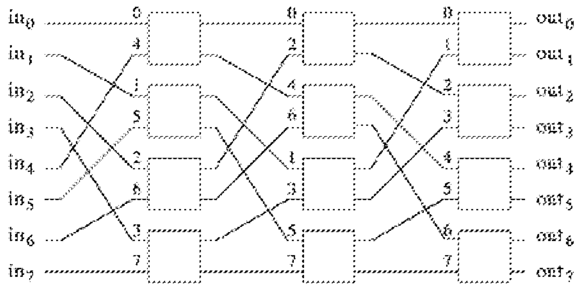
- Beneš network for $N = 8$, $n = 2$



- Cost: $C_{Benes} = 2N \cdot (2\log_2 N - 1)$
- A Beneš network ist **rearrangable**:
  - smallest network that allows the realization of all $N!$ permutations of the N inputs onto the N outputs
  - however a complex graph-theoretic algorithm required for the calculation of the switch positions

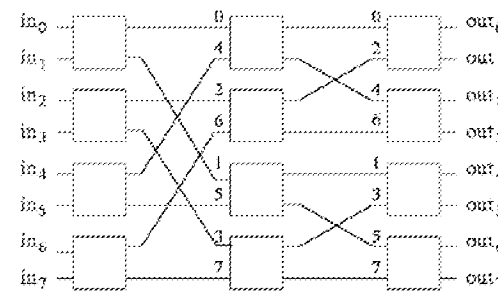
2.2 Dynamic interconnection networks (cont'd)

- **Omega network** (Lawrie, 1975):
  - $\log N$ switch stages
  - in each stage there are $m = N / k$ crossbars of size $k \times k$
  - the interconnection between two switch stage is either a butterfly (see next slide) or a shuffle function
  - *Example*: Omega network for $n = 8$, $k = 2$, with shuffle σ



2.2 Dynamic interconnection networks (cont'd)

- simple **routing algorithm** (here for k=2): bit d_i of the binary destination $d = (d_{n-1} \ldots d_i \ldots d_2\, d_1\, d_0)$ defines, which output must be used along the path in network stage i
- it is a **blocking** network, but many permutations can be realized
- *Example*: Omega network for $n = 8$, $k = 2$, with butterfly interconnect



- Omega network can also be constructed for arbitrary values of k

3 Switching Technologies

- **Circuit Switching**:
  - also called **connection-oriented** network service
  - each communication session consists of three phases:
    1) **establishment** of a continuous and exclusively used physical path between sender and receiver
    2) **data transfer**
    3) **release** of the connection
  - all intermediate nodes work as simple switching elements
  - all data elements use the same path from the sender to the receiver
  - the **total transmission time** for an m-byte message with a transmission rate or r bit/s is

$$T_{total} = T_{connect} + T_{latency} + \frac{8m}{r} + T_{release}$$

  - used for example in PSTN

3 Switching Technologies (cont'd)

- **Packet Switching**:
  - also called **connectionless** network service
  - each message is split into several packets (typically of a few thousand bits) that contain additional address and control information
  - each packet may take a different route from the sender to the receiver
  - consequently, the packets can have different latency and can arrive in a different order at the receiver node
  - the packets are reassembled at the receiver to the original message
  - if an m byte message (split into p packets, each with a header of h bytes) is transmitted at a rate of r bit/s and the overhead for routing each packet in a node is T_{route}, then the **total transmission time** for a message over a network in k hops is

$$T_{total} = k \cdot T_{route} + (k + p) \cdot (T_{transfer} + \frac{8}{r}\left\lceil \frac{m}{k} + h \right\rceil)$$

  - used for example in internet